UNCERTAINTIES OF TIME LINKS USED FOR TAI

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Abstract

There are three major elements in the construction of International Atomic Time (TAI): clocks, some means of comparing remote clocks, and a time-scale algorithm. The uncertainties of the time links used for TAI range from a few hundreds of picoseconds to a few tens of nanoseconds depending on the technique used. This paper provides a first rough estimation of the uncertainties of Type A and Type B in the time links used for TAI.

INTRODUCTION

There are three major elements in the construction of International Atomic Time (TAI): clocks, some means of comparing remote clocks (time transfer), and a time-scale algorithm. The uncertainties of time transfer can affect the stability of TAI. Two time-transfer techniques are used for the construction of TAI (see Figure 1): GPS common-view based on satellites of Global Positioning System (GPS), has been used since 1981 **[1,2]**; and TWSTFT (Two-Way Satellite Time Transfer), using the geostationary satellites INTELSAT, JCSAT-1B, and PAS-8, has been used since 1999 **[3]**. All TWSTFT links are backed up by GPS time links. GPS is generally used in common-view mode, using either older single-channel receivers (GPS CV) or newer multichannel receivers GPS (CV MCH) **[4]**. A few time links use so-called "GPS clock transportation" mode (GPS CT). Unlike TWSTFT, GPS time transfer is a one-way technique, which is more susceptible to perturbations than is TWSTFT. Atmospheric delays are the main limiting factors of GPS. Also, because GPS uses lower frequencies that TWSTFT, it is subject to greater noise.

A number of studies have examined the performances of GPS time transfer and TWSTFT **[1-3]**. Under optimum conditions, uncertainties of GPS common-view links range between 2 ns and 5 ns; those of TWSTFT range between a few hundreds of picoseconds and a nanosecond. The quality of TWSTFT has allowed for the first time the comparison of hydrogen masers distant even by several thousands of kilometers at their full level of performances. In practice, however, time links are often not operated under the best conditions. In this paper, we publish a first attempt of evaluation of the Type A and B uncertainties of TAI time links. Mainly because of lack of calibration, the Type B uncertainties of GPS links can reach several tens of nanoseconds. This underlines the urgent need for calibration of TAI time links.

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14. ABSTRACT
There are three major elements in the construction of International Atomic Time (TAI) clocks, some means of comparing remote clocks, and a time-scale algorithm. The uncertainties of the time links used for TAI range from a few hundreds of picoseconds to a few tens of nanoseconds depending on the technique used. This paper provides a first rough estimation of the uncertainties of Type A and Type B in the time links used for TAI.

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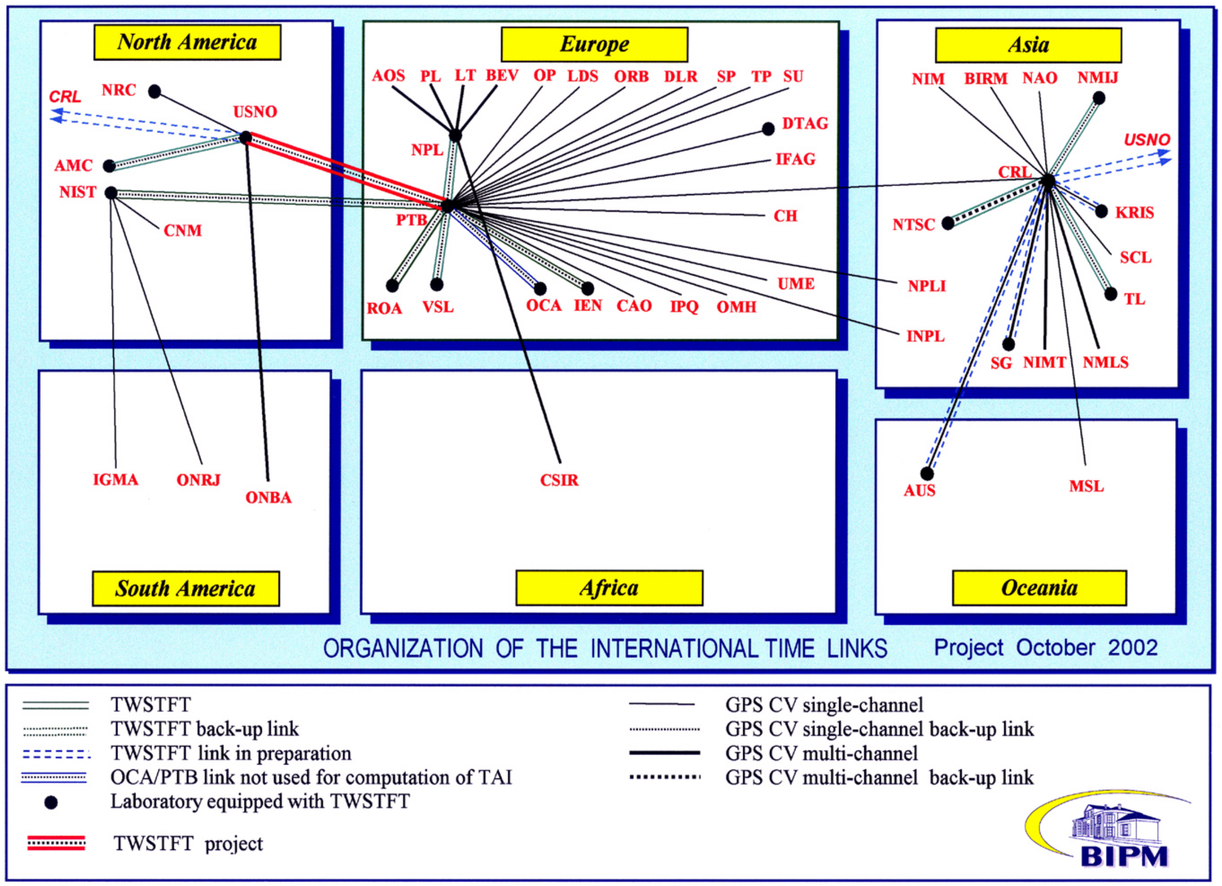

Figure 1. Summary of TAI time links. USNO/PTB TWSTFT Ku-band and its backup, the TWSTFT X-band link, will be introduced into TAI in January 2003.

EXPRESSION OF UNCERTAINTY FOR TAI TIME LINKS

Historically, in discussing uncertainties associated with different measurement techniques, descriptions such as “random” and “systematic” were used. However, in 1978 the International Committee for Weights and Measures (CIPM) requested the BIPM to look into the possibility of developing a consensus opinion on a means of expressing uncertainty in measurements. The results of these deliberations led to the publication of a guide **[5]** that was supported by seven international organizations.

The procedures contained in the *Guide to the Expression of Uncertainty in Measurement* are based on statistical analyses and/or external calibration measurements. The *Guide* recognizes the fact that certain uncertainties are subject to statistical measurements and others, which have sometimes been called systematic errors, are not statistical unless a sufficient quantity of them have been measured.

The statistically measured uncertainties are referred to as Type A uncertainties. They include:

- statistical analyses of a series of observations; and

- the internal uncertainty of measurement.

Type B uncertainties are usually evaluated by:

- means other than statistical analyses; and
- external calibration.

In many analyses, Type A uncertainties have been associated with measures of precision and Type B uncertainties with accuracy.

In Table 1 we provide a summary of the procedures we have chosen to determine Type A and B uncertainties of TAI time links. A more detailed description of these procedures is provided in the following section.

Table 1. Determination of Type A and B uncertainties of TAI time links.

Method	**Standard uncertainty**	
	Type A	**Type B**
GPS CV	Level of white phase noise modulation for [*UTC (k) – UTC (l)*] when the local UTC scales are based on H masers	Evaluated from: Calibration Coordinates Ionospheric delay Multipath Comparison with TWSTFT
TWSTFT	On-site comparison of two sets of TWSTFT equipment **[3]**	Evaluated from: Type of calibration Reciprocity or not of satellite path Comparison with TWSTFT

DETERMINATION OF TYPE A UNCERTAINTIES

For GPS common-view time transfer, where a local timescale UTC is based on a maser ensemble (or maybe even a single maser), a time deviation (TDEV) analysis reveals the transfer noise (Type A uncertainty) up to about 20 days. From 5 days to 20 days, this time transfer noise is typically about 2 ns for single-channel GPS receivers and somewhat less for multichannel receivers, when the receivers are used under optimum conditions. For example, for the NPL/NIST GPS single-channel time link, TDEV = 1.7 ns for an integration period τ_0 = 5 d. This value was derived from Figure 4. At NIST and NPL, the UTCs are realized by hydrogen masers.

For laboratories that do not have hydrogen masers, we cannot apply this kind of analysis, because the noise of the time transfer is masked by that of the clocks. With a high-performance HP 5071A clock, the TDEV at 5 days is about 2 ns, which is at or above the time transfer noise. Even with a small ensemble of

Cs clocks, we could not see the time transfer noise. Only masers are quiet enough, for periods up to 10 to 20 days, to show the transfer noise (see Figure 2). This is why, for GPS time links of laboratories not equipped with hydrogen masers, we have estimated the Type A uncertainties from an analysis of GPS time links of laboratories equipped with hydrogen masers.

For TWSTFT, Type A uncertainties from 0.2 ns to 0. 5 ns have been determined by on-site comparisons of two sets of TWSTFT apparatus **[3]**. For this evaluation, we could not use data from laboratories equipped with hydrogen masers, as noise of masers at 5 days can easily mask the TWSTFT time transfer noise.

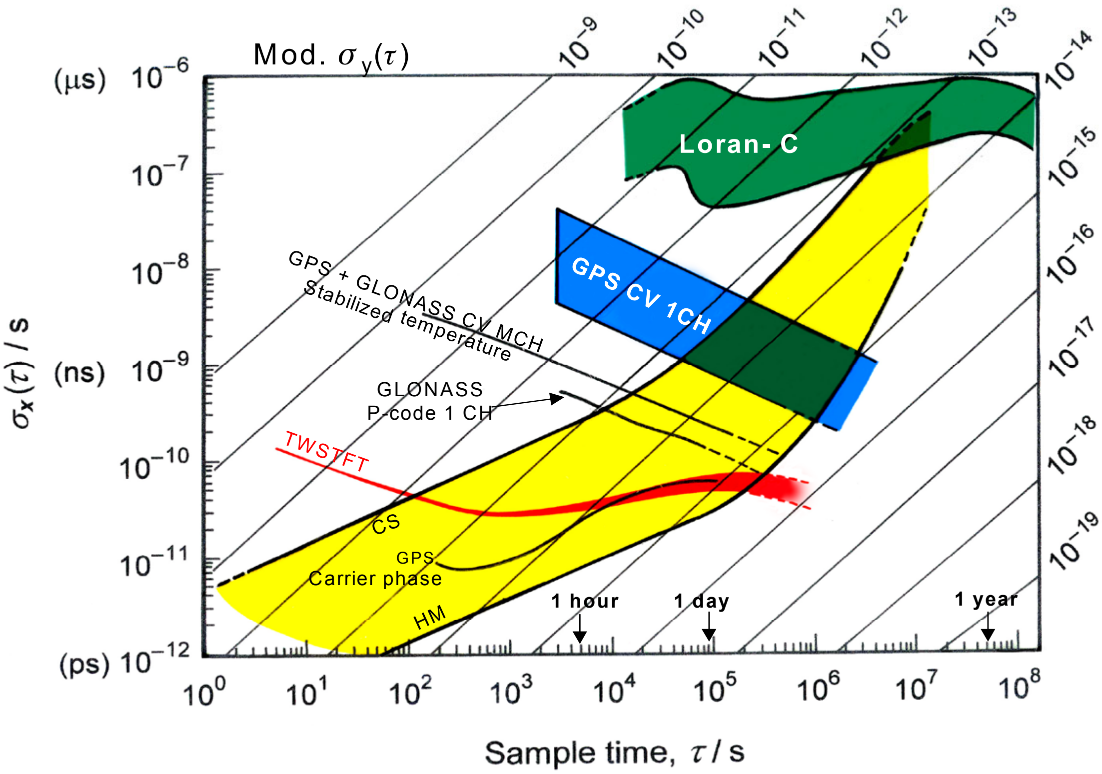

Figure 2. Comparison of time transfer techniques and typical clock performances.

DETERMINATION OF TYPE B UNCERTAINTIES

Certain uncertainties cannot be statistically measured or estimated, and must be evaluated through a process often called *calibration.* These are Type B uncertainties. For the needs of TAI, we apply differential calibration of GPS and TWSTFT timing equipment, realized through portable reference GPS or TWSTFT systems **[6-8]**.

The Type B uncertainty of GPS time transfer depends not only on the quality of the calibration. As GPS time transfer is a one-way system, it is subject to perturbations of the one-way path of the signal from

satellite to user. Thus, the quality of satellite ephemerides, user antenna coordinates, and mode of determining ionospheric delay should be taken into account when estimating the Type B uncertainties. The multipath around the antenna can also introduce a significant time shift **[9]**. GPS timing equipment is also sensitive to temperature. Seasonal systematic effects can sometimes be observed in the differences between GPS and TWSTFT.

Differential calibration of remote GPS time equipment is the basic technique for calibrating TAI GPS common-view time links. The stated uncertainty of such differential calibrations is about 3 ns for the period of calibration. Because the delay of GPS timing equipment is subject to seasonal changes, we adopt a more conservative value of 5 ns to characterize the Type B uncertainty of calibrated GPS time links. Over the last 15 years, a number of differential calibrations have been performed by the BIPM **[6]**, covering about one-third of the TAI GPS links. The GPS time equipment located at the NIST in Boulder, Colorado, and the Paris Observatory (OP) have been compared about 10 times; differential time corrections determined during these calibrations differ by no more than a few nanoseconds. This indicates the reproducibility that can be obtained when calibrations are performed under ideal conditions in laboratories where the GPS time equipment, including cables, is carefully maintained. It also gives some idea of the long-term stability of GPS time equipment (Table 2).

Table 2. Some past GPS calibrations between NIST and OP.

d is the differential time correction to be added to [UTC(NIST) – UTC(OP)], and $u(d)$ is the estimated standard uncertainty for the period of comparison.

Date	**d/ns**	**$u(d)$/ns**
July 1983	0	2
September 1986	1	2
October 1986	–1	2
January 1988	–4	3
April 1988	1	3
March 1994	3	2
March 1995	–4	1
May 1996	–1	2
May 2002	–5	3

Consistency between repeated calibrations is not found for all sites, however. Where discrepancies of 10 ns are found, these may be attributed to different responses of the receivers being compared, to seasonal changes of temperature, or to an unrecognized multipath effect. Other repeated calibrations have shown large discrepancies, sometimes of tens of nanoseconds; such changes probably arise from unrecorded changes, intended or not, in the GPS receiving hardware.

The Type B uncertainty of TWSTFT time transfer is mainly subject to the quality of calibration **[6,10]**. Differential calibration of TWSTFT equipment is only possible when a common transponder is used on a geostationary satellite. To date, only two TWSTFT links used for TAI have been differentially calibrated, with an estimated uncertainty of 1 ns **[11]**. One of these links, USNO/AMC, has been calibrated on several occasions, showing consistency better that 1 ns. Pending new TWSTFT calibrations, currently in

preparation, other TWSTFT links have been calibrated by GPS with an uncertainty of 5 ns, as stated above.

LONG-TERM COMPARISONS BETWEEN GPS AND TWSTFT

A valuable contribution to the evaluation of Type A and B uncertainties of time transfer techniques is a long-term comparison of various techniques **[7,8,12]**. Besides short-term noise (Type A uncertainties), a long-term comparison can reveal a constant offset between two techniques, and allows observation of their long-term behavior (Type B uncertainties).

There are currently (in December 2002) 12 TWSTFT links operational in Europe, North America, and the Pacific Rim. Ten of these are used for the construction of TAI. All these links are compared with GPS common-view time links and are published in the BIPM *TWSTFT Reports* **[12]**. A number of the TWSTFT links have been operational for 3 years already. A typical comparison for NPL/NIST, distant by about 8,000 km, for the MJD period 51510-51970 is shown in Figure 3. The NPL/NIST TWSTFT link was calibrated by GPS. The TWSTFT data, collected during three sessions per week (Monday, Wednesday, and Friday), were linearly interpolated for TAI standard dates (MJD ending in 4 and 9). The GPS common views were computed using IGS precise ephemerides and IGS ionospheric maps, then smoothed and interpolated for the standard dates. During the period of the comparison, we do not observe any departure or seasonal effect. The rms of the differences between two the methods for the period of comparison is 2.1 ns. The estimated uncertainty of the TWSTFT link is below 1 ns, and that of GPS is 2.5 ns. Thus, we believe that most of the observed noise in the differences between the two methods is due to GPS common view, and this is confirmed by analysis of the frequency stability of [*UTC* (NPL) – *UTC* (NIST)] (Figure 4). The GPS common-view data show white phase noise due to method of comparison, up to averaging times of 20 days. The TWSTFT data are showing white frequency noise, characteristic of clock behavior, already for averaging times of 5 days. This means that, for averaging times of 5 days or more, we no longer see any more noise due to TWSTFT. In other words, two hydrogen masers, realizing UTC (NPL) and UTC (NIST) and located at a distance of 8,000 km, can be compared by TWSTFT without any noise of time transfer for averaging times of 5 days.

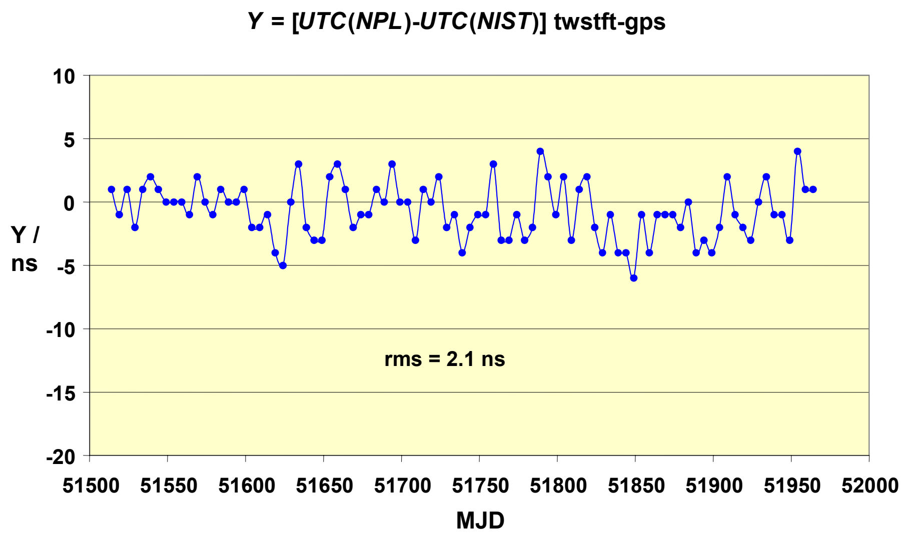

Figure 3. Differences between TWSTFT and GPS C/A-code common view for the NPL/NIST link.

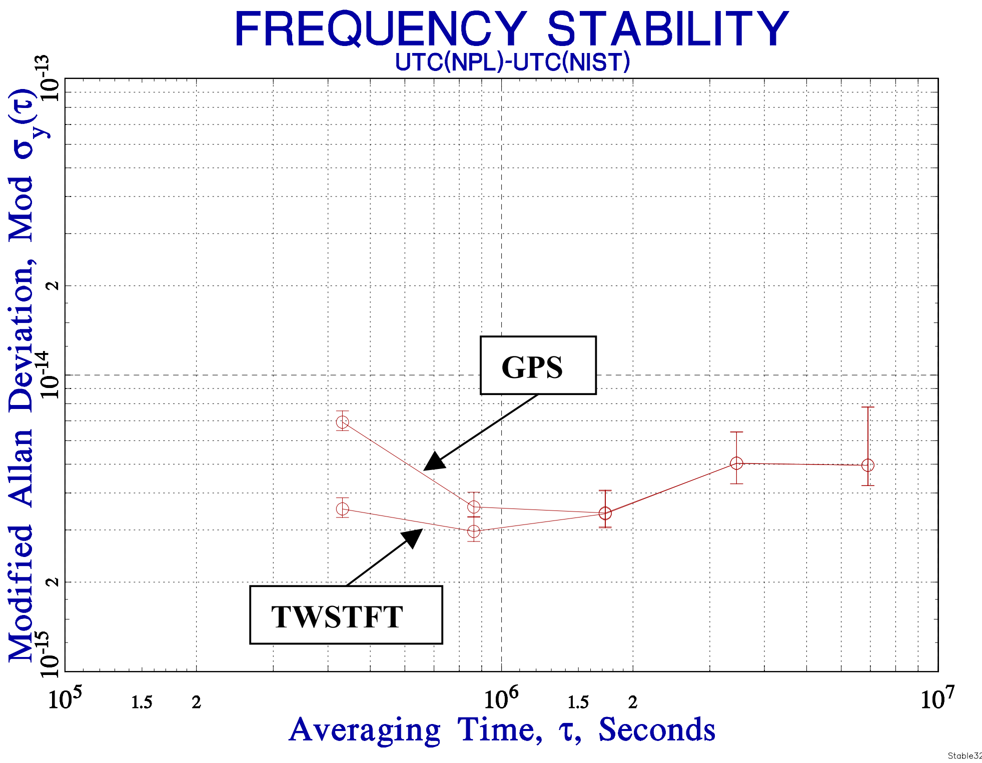

Figure 4. Frequency stability of [*UTC (NPL) – UTC (NIST)*] by GPS CV and by TWSTFT. UTCs at NPL and NIST are realized by hydrogen masers.

STANDARD UNCERTAINTIES OF TIME LINKS USED FOR TAI

Using the approach described above together with the information available at the BIPM, we have estimated the Type A and B uncertainties of all the TAI time links (Tables 3 and 4). To estimate Type B uncertainties, we rely mainly on the quality of the calibrations, their age, and their repeatability. Knowledge of various types of GPS time receiver was also helpful for this estimation. Yet, this first attempt to estimated uncertainties of TAI time links is certainly imperfect. We will continue to refine these estimations and in the near future will begin to publish monthly uncertainties of the TAI links. The ultimate goal, however, is to publish uncertainties of [UTC – UTC (*i*)] in BIPM's *Circular T*.

To conclude, we stress that most of the TAI time links have large Type B uncertainties due to the lack of calibration of the time transfer equipment. The BIPM will continue its GPS calibration campaigns with a new generation of temperature-stabilized multichannel receivers. The calibration of time links is a long process, and the recent involvement of regional metrology organizations is welcomed. Permanent calibrations of TWSTFT links using a portable TWSTFT station will also be started soon.

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The authors express their thanks to Tom Parker of NIST for fruitful exchanges during the preparation of this paper.

Table 3. Preliminary evaluation of standard uncertainties of TAI TWSTFT primary links and their backups.

Lab(i)–Lab(j)	Primary Link	Stand. Uncertainty/ns			Back-up Link	Stand. uncertainty/ns		
		A	B	Combined		A	B	Combined
PTB–USNO*	TWSTFT/Ku	0.3	1	1	TWSTFT/X	0.3	1	1
AMC–USNO	TWSTFT	0.3	1	1	GPS CV	2.5	5	6
NPL–USNO	TWSTFT	0.3	5	5	GPS CV MCH	1.5	5	5
PTB–NIST	TWSTFT	0.3	5	5	GPS CV	2.0	5	5
PTB–VSL	TWSTFT	0.3	5	5	GPS CV	2.0	5	5
PTB–NPL	TWSTFT	0.3	5	5	GPS CV	2.5	5	6
PTB–ROA	TWSTFT	0.3	5	5	GPS CV	2.5	5	6
PTB–IEN	TWSTFT	0.3	5	5	GPS CV	2.5	5	6
CRL–NMIJ	TWSTFT	0.3	10	10	GPS CV	2.5	10	10
CRL–JATC	TWSTFT	0.3	10	10	GPS CV	4.0	10	11
CRL–NTSC	TWSTFT	0.3	10	10	GPS CV MCH	4.0	10	11
CRL–TL	TWSTFT	0.3	10	10	GPS CV	3.5	10	11

* PTB/USNO TWSTFT Ku-band link and its backup, TWSTFT X-band link, will be introduced into TAI in January 2003.

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Table 4. Preliminary evaluation of standard uncertainties of TAI GPS links.

Lab(i)–Lab(j)	Link	Standard uncertainty/ns		
		A	B	Combined
NPL–AOS	GPS CV MCH	1.5	5	5
NPL–LT	GPS CV MCH	1.5	5	5
NPL–PL	GPS CV MCH	1.5	5	5
NPL–BEV	GPS CV MCH	1.5	5	5
NPL–CSIR	GPS CV MCH	1.5	10	10
CRL–AUS	GPS CV MCH	2.5	10	10
USNO–ONBA	GPS CV MCH	1.5	15	15
CRL–NMLS	GPS CV MCH	4.0	20	20
CRL–NIMT	GPS CV MCH	4.0	20	20
CRL–NMLS	GPS CV MCH	4.0	20	20
CRL–SG	GPS CV MCH	4.0	20	20
CRL–BIRM	GPS CV MCH	4.0	20	20
PTB–OP	GPS CV	2.0	5	5
PTB–CRL	GPS CV	2.0	5	5
PTB–TP	GPS CV	2.0	5	5
PTB-CH	GPS CV	2.0	5	5
PTB–ORB	GPS CV	2.0	5	5
PTB-IFAG	GPS CV	2.5	5	5
PTB–SU	GPS CV	2.5	5	6
PTB–SP	GPS CV	3.5	5	6
PTB–INPL	GPS CV	2.5	10	10
PTB–LDS	GPS CV	2.5	10	10
PTB–OCA	GPS CV	2.5	10	10
PTB–OMH	GPS CV	2.5	10	10
PTB–SMU	GPS CV	2.5	10	10
PTB–UME	GPS CV	2.5	10	10
USNO–NRC	GPS CV	2.5	10	10
CRL–KRISS	GPS CV	2.5	10	10
CRL–NAO	GPS CV	2.5	10	10
NIST-CNM	GPS CV	2.5	10	10
PTB–DTAG	GPS CV	2.5	10	10
PTB–CAO	GPS CV	2.5	20	20
PTB–IPQ	GPS CV	2.5	20	20
CRL–NIM	GPS CV	2.5	20	20
PTB–DLR	GPS CV	4.0	20	20
CRL–MSL	GPS CV	4.0	20	20
PTB–NPLI	GPS CV	4.0	20	20
CRL–SCL	GPS CV	3.5	30	30
NIST–ONRJ	GPS CV	10.0	50	51
NIST–IGMA	GPS CT	10.0	50	51
PTB–NIMB	GPS CT	10.0	50	51
PTB–NMC	GPS CT	10.0	50	51

QUESTIONS AND ANSWERS

MARC WEISS (National Institute of Standards and Technology): You reported the variation of about 20 nanoseconds between two-way and GPS, and you say it is due to GPS. How do you know that?

WLODZIMIERZ LEWANDOWSKI: That is a question for the laboratory, I do not want to tell exactly which laboratory it is. My comparisons with the laboratory with all their time techniques available, it could be that it was GPS. It was quite easy to find. It was not a big problem. The use of two-way allowed us to observe this phenomenon.

WEISS: It is not that way on all GPS two-way links, though. You do not see 20 nanoseconds excursions between GPS and two-way in general.

LEWANDOWSKI: No, it was a very special case, but still with the two methods, we could observe it. What happened would maybe have not been noticed without the two methods.

GERARD PETIT (Bureau International des Poids et Mesures): Just one short comment. We certainly have to refine our method to estimate the statistical uncertainty of the GPS common- view links. In a lot of cases, the 5-day points are not a good indicator of white phase noise anymore. So, in some cases, you see the clocks at 5-day and in some cases you don't. We have to refine this method.

LEWANDOWSKI: Yes, of course. We have to work case by case. This is the very first draft of such uncertainties. I believe that we should also write to each laboratory and ask several standard questions about the situations in their laboratories, the latest calibration, and the evaluations and the feeling of the laboratory itself about the quality of the GPS setup. To publish these numbers is a little bit embarrassing, because many laboratories we have seen have large uncertainties. So we wouldn't like to show this before we work this out with the each of the laboratories.